

Impact of Lithium Battery Recycling and Second-Life Application on Minimizing Environmental Waste [†]

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Abstract: In the prospect of greener transportation means and global emission limitations for the protection of the environment, the electric vehicles' market share is constantly increasing. It is expected that 32% of new vehicles sold in 2030 will be pure electric or plug-in hybrids. As all electric vehicles utilize lithium batteries to power the powertrain, the need for rare earth materials, like lithium or nickel, exceeds the planet's ability to provide the required capacities. Additionally, even though lithium-ion batteries provide high energy density, they have some disadvantages like a limited range and durability at high-temperature operation. This issue can be improved greatly with the implementation of a hybrid energy storage system consisting of batteries and ultracapacitors. In this paper, the power efficiency of this storage system will be analyzed. Finally, when the cells reach below a specific capacity threshold, they can be removed from the vehicle to be installed in renewable energy plants for storing surplus energy production. Therefore, environmental waste is minimized while simultaneously assisting grid power demands, before being recycled to recover a portion of the rare metals used.

Keywords: environment; HESS; lithium; minerals; recycling; pollution; metals; waste



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1. Introduction

Transportation is one of the main sectors affecting pollution and climate change across the globe. Greenhouse gas (GHG) emissions grew by 2.1% or 137 Megatons last year, with the potential to reach 150 Megatons if the trend for hybrid electric or pure electric vehicles is not deployed [1]. The electric vehicles' (EV) market share is constantly increasing, reaching 14% of total sales in 2022 and an expected 32% by 2030. Renowned manufacturers like Volkswagen, Mercedes, and Honda are expected to provide almost 100% of their fleet as electric with approximately 20 million units to be sold per year by 2025, and an estimated battery production capacity of one Gigawatt-Hours [2]. This complies with the jurisdictions made by governments that only zero emission vehicles are applicable after 2040 as means of zero-emission transportation. Other measures, including carbon taxes, the exploitation of biofuels, extended renewable energy production, and the complete adoption of green public transportation are considered essential in this direction [3]. Moreover, as light-duty vehicles are projected to almost 50% of total transportation resources required, economic subsidiaries are offered as supportive actions assisting people to buy an EV.

The European green deal is a big project in the decarbonizing prospectus of the European union [4]. The current agreement states that GHGs are to be reduced by 40% by 2030, while the aim of this directive is to annihilate carbon emissions by 2050, focusing mainly on urban transportation and city traffic. Electric vehicles evidently arise to be the solution, especially for residential areas with heavy traffic. In Europe, it is suggested to minimize emissions while providing extra benefits like the limited need for maintenance, noiseless

operation, full power at low speeds, and energy regeneration [5]. Additionally, while there are many technical and social difficulties to overcome for complete EV adoption, there are certain directions that can be followed to work through those issues [6], specifically:

- Limited range from 100 km to 250 km per charge can be overcome with fast charging or the exploitation of a more sophisticated energy storage
- Lack of a universal connector is addressed globally via the adoption of the International Combined Charging System (CSS) or CHAdeMO protocols
- Consumer Behavior and the lack of intention to purchase an EV requires more intensives and remains a complex challenge

2. Lithium Batteries: Application, Issues, and Hybridization

Lithium batteries are the main source of every electronic component used widely in daily applications like torches, personal computers, and smartphones. Electric vehicles use lithium batteries to provide energy to the powertrain and utilities like climate control, sound systems, and secondary electronics. They consist of four main components [7]: Anode, Cathode, Electrolyte, and Separator. During discharge, lithium ions flow from the anode to the cathode, and comes the opposite action while charging. The electrolyte assists that flow, as well as the separator, protects the two parts of the cell from a short circuit. There is a wide variety of lithium chemistries applied for manufacturing depending on the cathode material [8]:

- Lithium Iron Phosphate (LFP), which is massively exploited for electronic devices and electric vehicles now due to low cost and degradation but are less powerful
- Lithium Nickel-Cobalt-Aluminum Oxide (NCA) that inherits greater energy density and a faster charging performance, but requires unsustainable raw materials and suffers from a high-thermal runaway risk
- Lithium Nickel-Manganese-Cobalt (NCM), which has a lower discharge range and lower life cycles but higher energy density

LFP cells generate less GHG emissions than the other two chemistries, with the total value varying depending on the production region and the type of electricity being consumed [9]. As Europe utilizes renewables more than other countries, especially China or the USA, it is considered ideal for production, but lithium deposits are scarce. Additionally, as LFP does not require expensive minerals like nickel or cobalt, they are safer, cheaper, and have a longer lifespan, so manufacturers prefer them for their applications. Altogether, batteries' market share is growing rapidly and is expected to reach 280 billion USD by 2030. However, certain limitations like thermal management, low discharge rate, limited power density, and cycle life have to be addressed [10].

The rapid charging of lithium cells increases temperature, causing lithium deposition at the cathode, and thus, less ions are available to flow, leading to capacity reduction [11]. Cycles are moderate, 2000–3000 in total, while the exploitation of regenerative braking is limited due to the unavailability to handle the high-frequency currents. Lastly, cells are stressed rapidly when providing high power at peak loads, causing increased temperature, which is identified as the main parameter affecting aging. To encounter these constraints, a hybrid energy storage system consisting of batteries and supercapacitors is implemented. Supercapacitors are components with a high capacitance, power density, and lifespan, but their reduced energy density makes them insufficient as a standalone power source; thus, they are utilized as auxiliary to the battery [10,12]. They cover the high peak load conditions of an EV like rapid acceleration, climate control, and filtering high frequency currents during charging without issues, where they can be recharged immediately for over 3 million life cycles, compared to a typical count of 3000 cycles for the battery, so they are preferred in applications like grid storage and power smoothing. Also, recent studies reveal this source potential as a reduction in size and cost up to 25% is achieved for EVs [13].

3. Mining, Recycling and Second Life Exploitation

3.1. Mining

As lithium batteries are essential for the majority of electronics and devices with over 273 GWh produced only in 2021, the need for mining lithium and other minerals is heavily growing, stretching the planet's ability to provide them, which may lead to supply risks [14,15]. Rare earth materials like lithium, nickel, cobalt, and manganese account for 76% of the production cost. While lithium is still adequately available, the expensive cobalt can be found in countries with low economies, like Kongo where child miners are forced to extract it. In addition, aluminum manufacturing and nickel mining are energy intensive, thus increasing the total cost while waste is generated, polluting the water supplies and land and further deploying serious environmental impacts [16]. Trees are cut down, the local fauna becomes extinct, and large amounts of water and energy are required, further enhancing the negative environmental footprint of mining. Finally, tourism and agriculture sectors are threatened due to the huge ecological disruption.

Lithium production has been surpassed more than five times in the last 10 years, mainly found in Chile, China, the USA, and Australia [17]. It can be found in many applications like ceramics, polymers, metallurgy, and mainly batteries. However, the leading area for lithium usability, over 50%, are electric vehicles. For example, while an electronic device needs 2 to 10 g of lithium, an EV battery pack requires up to 15 kg of the mineral. This demand is directly affecting the price of the metal, which has already significantly increased over four times from 2010 to 2021 [18]. Research has been focused on two distinct options: (a) detecting new lithium sources via satellite and machine learning methods to cover the necessary resources and (b) harvesting lithium from new eco-friendly small source brines or wastewater but with lower production [19].

3.2. Recycling

Opening new mines can be intriguing or even forbidding due to the environmental challenges it introduces and the opposition of the local society. Additionally, as the need for lithium batteries is constantly growing, eco waste has also increased radically [20,21]. Special treatment is required for the recycling process, especially for the valuable metals, mainly cobalt and lithium, contained in the aged cells that can be reused in new parts and bring added value. Manufacturers are now focusing on new techniques and solvents via hydrometallurgy processes to regain as much minerals as possible. Governance assists in that effort, for instance, the United States of America is about to administer 75 million USD to support a brand-new project for lithium recycling [16].

Lately, studies have shown that the complete separation of the two metals has almost been achieved, and even the recovery of nickel is possible, although in small quantities. The reduction in the net impact caused by lithium mining is achievable, even though the current reserves of lithium are not expected to cause any short-term issues. To ensure the sustainability of the EV industry, the rule of the 3R system (recycle, reduce, and reuse) has to be followed [22]. Batteries must be uninstalled from the chassis steel cage, dismantled, tested, diagnosed for any possible errors, and then recycled. The three main recycling methods are:

1. Pyrometallurgy, using a high-temperature furnace to burn the polymers, leaving only pure metals
2. Hydrometallurgy through dissolving with aqueous solutions, and
3. Direct recycling, with hands-on removal of the components

Table 1 below summarizes the recycling methods separately:

Table 1. Comparison of recycling methods as shown at [22].

Parameters	Pyrometallurgy	Hydrometallurgy	Direct Recycling
Simplicity	Very High	Medium	Low
Energy efficient	Low	Medium	Medium
Production Cost	Very High	Medium	Low
Rare earth materials recovery	Adequate	Very High	High

Each method is preferred at different materials, for example, hydrometallurgy is perfect for cobalt-rich cathodes, with the ability to recover over 96% of the metal, whereas direct recycling is preferable for LFP batteries due to the absence of cobalt and nickel [23]. Pyrometallurgy is cost-sufficient and a very simple process, as no pre-production process is needed but has a high energy consumption. Nevertheless, all methods seem capable of providing the massive requirements of those materials in the EV industry and support the high demand, but the alternative methods for full recyclability are essential. Additionally, scale economy and greenhouse gas limitation are still matters of concern.

3.3. Second-Life Batteries

Recent studies have shown another purpose for the end-of life batteries of EV as auxiliary energy sources, where storage is required. For example, they can be installed in renewable energy stations (RES), especially solar and wind, where the power output due to weather is highly unstable [24,25]. Even though load behavior can be forecasted at a high safety level, the power system flexibility is essential to avoid any failures or bottlenecks, especially with the impact of EV charging at different time periods [25]. When RES production is high, the batteries can store the excess energy, and during peak hours, when renewables are usually shut down, we can supply the grid to cover the massive energy demand [26]. As renewables are highly penetrating the energy generation map and are expected to reach 60% of the supply by 2040, day-ahead planning is deemed crucial [27].

The benefits of utilizing used battery packs as power banks are excessive. In total, battery lifespan is shown to increase by 35%, while limiting the need, hence the cost, for new batteries that would be needed for the same purpose [28]. Deployed for EVs, the battery should operate only for 10–15 years maximum, typically preserving 70–80% of their capacity, as exaggerating this limit will damage the cell internally while the range is greatly reduced [29]. Due to the high frequency currents and lithium deposits in the cathode, the separator and electrolyte are susceptible to short-circuit or a total breakdown [30]. On the other side, the battery's useful life can be doubled, reaching 30 years, if second-life applications especially are considered [29,30]. Of course, not all cells are eligible for second-life use, as ageing parameters have to be studied extensively. Additionally, some battery modules have to be remanufactured (repowering), as certain cells may be faulty or in need of servicing before being reapplied for second use as auxiliary sources [31].

4. Comparison of the Two Methods: Recycling and Second Use

As previously discussed, both recycling and second use are suggested as excellent options for end-of-life batteries. However, both seem to have limitations if applied separately. Some battery models cannot be reused, and others are in great condition and recycling would enduce power losses. Therefore, if the model of circular economy, shown in Figure 1, is followed, the total economy is massively increased. For a typical EV battery at 50 kWh, maintaining 70% of total capacity and reaching 35 kWh before being reused as a second life until 25–30 years of operation, the total savings, including the initial cost of a brand-new battery that would be purchased and the metals recycled, equal to half the price of the brand-new battery [14,28]. Additionally, the utilization of the battery as a HESS will save 20% more capacity as the cells would be less stressed, due to the assistance of supercapac-

itors, whereas the system would be 25% cheaper [13,32] and result in a more powerful, compact system with a better lifespan estimated at over 35 years.

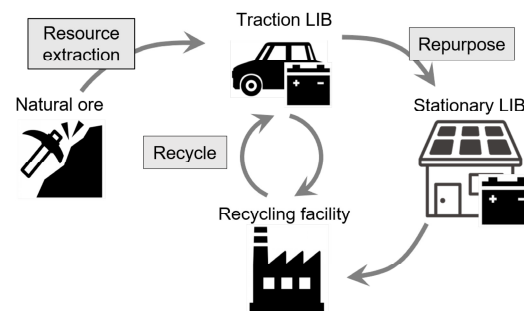


Figure 1. Battery Circular Economy by [32].

5. Conclusions

The need for a greener environment is crucial and the adoption of electric vehicles is a major step in that direction. As mining has a sufficient impact on the planet, prolonging the lifespan of lithium batteries by merging them with ultracapacitors as a hybrid energy system defies the drawbacks that they inherit. Furthermore, the circular economy concept doubles the operational life of the battery while providing power flexibility to the grid, as the energy output of renewables becomes more stable and predictable. It can be summarized that over 50–60% of the typical battery cost can be saved, reaching almost 35 years of use, and limiting total waste. Finally, the battery can be recycled and rare earth metals like cobalt and nickel can be recovered, limiting the need for relentless mining that leads to environmental footprints and the disruption of the local ecosystem.

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References

1. IEA. Available online: <https://www.iea.org/reports/co2-emissions-in-2022> (accessed on 1 May 2023).
2. ICCT. Available online: <https://theicct.org/publication/how-technology-recycling-and-policy-can-mitigate-supply-risks-to-the-long-term-transition-to-zero-emission-vehicles/> (accessed on 1 May 2023).
3. Zhang, S.; Witlox, F. Analyzing the Impact of Different Transport Governance Strategies on Climate Change. *Sustainability* **2020**, *12*, 200. [CrossRef]
4. Haas, T.; Sander, H. Decarbonizing Transport in the European Union: Emission Performance Standards and the Perspectives for a European Green Deal. *Sustainability* **2020**, *12*, 8381. [CrossRef]
5. Rietmann, N.; Hügl, B.; Lieven, T. Forecasting the Trajectory of Electric Vehicle Sales and the Consequences for Worldwide CO₂ Emissions. *J. Clean. Prod.* **2020**, *261*, 121038. [CrossRef]
6. Ghosh, A. Possibilities and Challenges for the Inclusion of the Electric Vehicle (EV) to Reduce the Carbon Footprint in the Transport Sector: A Review. *Energies* **2020**, *13*, 2602. [CrossRef]
7. Rangarajan, S.S.; Sunddharaj, S.P.; Sudhakar, A.; Shiva, C.K.; Subramaniam, U.; Collins, E.R.; Senjyu, T. Lithium-Ion Batteries—The Crux of Electric Vehicles with Opportunities and Challenges. *Clean Technol.* **2022**, *4*, 908–930. [CrossRef]
8. Xu, C.; Steubing, B.; Hu, M.; Harpprecht, C.; Van Der Meide, M.; Tukker, A. Future Greenhouse Gas Emissions of Automotive Lithium-Ion Battery Cell Production. *Resour. Conserv. Recycl.* **2022**, *187*, 106606. [CrossRef]

9. Dai, Q.; Kelly, J.C.; Gaines, L.; Wang, M. Life Cycle Analysis of Lithium-Ion Batteries for Automotive Applications. *Batteries* **2019**, *5*, 48. [\[CrossRef\]](#)
10. Khalid, M. A Review on the Selected Applications of Battery-Supercapacitor Hybrid Energy Storage Systems for Microgrids. *Energies* **2019**, *12*, 4559. [\[CrossRef\]](#)
11. Han, X.; Lu, L.; Zheng, Y.; Feng, X.; Li, Z.; Li, J.; Ouyang, M. A Review on the Key Issues of the Lithium Ion Battery Degradation among the Whole Life Cycle. *eTransportation* **2019**, *1*, 100005. [\[CrossRef\]](#)
12. Rimpas, D.; Kaminaris, S.D.; Piromalis, D.; Vokas, G. *A Review on Electric Vehicle Hybrid Energy Storage Systems*; AIP Publishing: Athens, Greece, 2022; p. 020091.
13. Rimpas, D.; Kaminaris, S.D.; Piromalis, D.; Vokas, G.; Papageorgas, P. *Design and Implementation of a Small-Scaled Hybrid Storage System for Optimal Sizing in Electric Vehicles*; AIP Publishing: Metz, France, 2023; p. 020007.
14. Philippot, M.; Alvarez, G.; Ayerbe, E.; Van Mierlo, J.; Messagie, M. Eco-Efficiency of a Lithium-Ion Battery for Electric Vehicles: Influence of Manufacturing Country and Commodity Prices on GHG Emissions and Costs. *Batteries* **2019**, *5*, 23. [\[CrossRef\]](#)
15. Habib, K.; Hansdóttir, S.T.; Habib, H. Critical Metals for Electromobility: Global Demand Scenarios for Passenger Vehicles, 2015–2050. *Resour. Conserv. Recycl.* **2020**, *154*, 104603. [\[CrossRef\]](#)
16. Luong, J.H.T.; Tran, C.; Ton-That, D. A Paradox over Electric Vehicles, Mining of Lithium for Car Batteries. *Energies* **2022**, *15*, 7997. [\[CrossRef\]](#)
17. Graham, J.D.; Rupp, J.A.; Brungard, E. Lithium in the Green Energy Transition: The Quest for Both Sustainability and Security. *Sustainability* **2021**, *13*, 11274. [\[CrossRef\]](#)
18. Garcia, L.V.; Ho, Y.-C.; Myo Thant, M.M.; Han, D.S.; Lim, J.W. Lithium in a Sustainable Circular Economy: A Comprehensive Review. *Processes* **2023**, *11*, 418. [\[CrossRef\]](#)
19. Cardoso-Fernandes, J.; Teodoro, A.C.; Lima, A.; Perrotta, M.; Roda-Robles, E. Detecting Lithium (Li) Mineralizations from Space: Current Research and Future Perspectives. *Appl. Sci.* **2020**, *10*, 1785. [\[CrossRef\]](#)
20. Sobianowska-Turek, A.; Urbańska, W.; Janicka, A.; Zawislak, M.; Matla, J. The Necessity of Recycling of Waste Li-Ion Batteries Used in Electric Vehicles as Objects Posing a Threat to Human Health and the Environment. *Recycling* **2021**, *6*, 35. [\[CrossRef\]](#)
21. Kavanagh, L.; Keohane, J.; Garcia Cabellos, G.; Lloyd, A.; Cleary, J. Global Lithium Sources—Industrial Use and Future in the Electric Vehicle Industry: A Review. *Resources* **2018**, *7*, 57. [\[CrossRef\]](#)
22. Harper, G.; Sommerville, R.; Kendrick, E.; Driscoll, L.; Slater, P.; Stolkin, R.; Walton, A.; Christensen, P.; Heidrich, O.; Lambert, S.; et al. Recycling Lithium-Ion Batteries from Electric Vehicles. *Nature* **2019**, *575*, 75–86. [\[CrossRef\]](#)
23. Tao, Y.; Rahn, C.D.; Archer, L.A.; You, F. Second Life and Recycling: Energy and Environmental Sustainability Perspectives for High-Performance Lithium-Ion Batteries. *Sci. Adv.* **2021**, *7*, eabi7633. [\[CrossRef\]](#)
24. Impram, S.; Varbak Nese, S.; Oral, B. Challenges of Renewable Energy Penetration on Power System Flexibility: A Survey. *Energy Strategy Rev.* **2020**, *31*, 100539. [\[CrossRef\]](#)
25. Kapustin, N.O.; Grushevenko, D.A. Long-Term Electric Vehicles Outlook and Their Potential Impact on Electric Grid. *Energy Policy* **2020**, *137*, 111103. [\[CrossRef\]](#)
26. Chen, T.; Jin, Y.; Lv, H.; Yang, A.; Liu, M.; Chen, B.; Xie, Y.; Chen, Q. Applications of Lithium-Ion Batteries in Grid-Scale Energy Storage Systems. *Trans. Tianjin Univ.* **2020**, *26*, 208–217. [\[CrossRef\]](#)
27. Zsiborács, H.; Baranyai, N.H.; Vincze, A.; Zentkó, L.; Birkner, Z.; Máté, K.; Pintér, G. Intermittent Renewable Energy Sources: The Role of Energy Storage in the European Power System of 2040. *Electronics* **2019**, *8*, 729. [\[CrossRef\]](#)
28. Canals Casals, L.; Barbero, M.; Corchero, C. Reused Second Life Batteries for Aggregated Demand Response Services. *J. Clean. Prod.* **2019**, *212*, 99–108. [\[CrossRef\]](#)
29. Haram, M.H.S.M.; Lee, J.W.; Ramasamy, G.; Ngu, E.E.; Thiagarajah, S.P.; Lee, Y.H. Feasibility of Utilising Second Life EV Batteries: Applications, Lifespan, Economics, Environmental Impact, Assessment, and Challenges. *Alex. Eng. J.* **2021**, *60*, 4517–4536. [\[CrossRef\]](#)
30. Martinez-Laserna, E.; Sarasketa-Zabala, E.; Villarreal Sarria, I.; Stroe, D.-I.; Swierczynski, M.; Warnecke, A.; Timmermans, J.-M.; Goutam, S.; Omar, N.; Rodriguez, P. Technical Viability of Battery Second Life: A Study From the Ageing Perspective. *IEEE Trans. Ind. Appl.* **2018**, *54*, 2703–2713. [\[CrossRef\]](#)
31. Ahmadi, L.; Young, S.B.; Fowler, M.; Fraser, R.A.; Achachlouei, M.A. A Cascaded Life Cycle: Reuse of Electric Vehicle Lithium-Ion Battery Packs in Energy Storage Systems. *Int. J. Life Cycle Assess.* **2017**, *22*, 111–124. [\[CrossRef\]](#)
32. Kosai, S.; Takata, U.; Yamasue, E. Global Resource Circularity for Lithium-Ion Batteries up to 2050: Traction and Stationary Use. *Mining* **2022**, *2*, 449–462. [\[CrossRef\]](#)

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